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INSTITUTE FOR DEFENSE ANALYSES

**Modeling and Simulation  
for Manufacturing**

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## **PREFACE**

This document was prepared under the Institute for Defense Analyses Independent Research Program task entitled "Manufacturing Modeling and Simulation."

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## CONTENTS

PREFACE .....	iii
SUMMARY .....	S-1
I. STATE OF THE ART IN MANUFACTURING MODELING AND SIMULATION .....	I-1
A. Well-Developed Tools .....	I-2
B. Significant Limitations .....	I-4
II. USAGE OF MODELING AND SIMULATION.....	II-1
A. Lean Aerospace Surveys .....	II-1
1. Requirements Generation .....	II-1
2. Cost Modeling .....	II-2
3. Process Capability Databases .....	II-4
B. Case Study: Lockheed Martin .....	II-6
C. Case Study: Hewlett-Packard .....	II-7
III. SIMULATION SOFTWARE TOOLS .....	III-1
A. Features and Capabilities.....	III-1
B. Comparison of Seven Tools .....	III-3

## APPENDICES

A. References.....	A-1
B. Glossary .....	B-1

## TABLES

1 Seven Simulation Software Packages .....	III-3
2 Modeling Constructs and Procedures.....	III-3
3 General Capabilities of Simulation Software.....	III-4
4 Statistical Features of Simulation Software .....	III-5
5 Optimization Features of Simulation Software.....	III-6

## SUMMARY

This paper provides an overview of manufacturing modeling and simulation, which includes applications to improve the performance, manufacturability, quality, and cost of products. Through modeling and simulation, developers can optimize designs and processes without the cost of building and testing physical prototypes or shops.

The paper examines reviews of the emerging state of the art in manufacturing modeling and simulation, studies based on surveys of government and industry product development offices, and information from companies that use modeling and simulation directly to enhance their product development efforts.

The research finds that manufacturing modeling and simulation is making great progress toward the vision of a rich toolset that fully integrates with design tools and supports a smooth flow of useful information throughout the organization. Software and technologies are generally being developed only for specific applications and are not well integrated with existing products. Success stories include knowledge-based advisors; tools to improve product quality and make processes more effective in the semiconductor industry; and digital, model-based design and manufacturing techniques in the automotive and aerospace industries. Some of the more significant factors limiting the effectiveness of manufacturing modeling and simulation tools are the poorly understood physics of some manufacturing processes and the lack of interoperability among tools.

Surveys of industry and government show that manufacturing modeling and simulation is used most frequently for requirements generation. Cost models are difficult to build, but when they are used in conjunction with other tools they yield significant benefits. Finally, most firms interviewed had some sort of process capability database and believed in its potential to improve design and manufacturability but did not effectively use the databases because of a number of technical and organizational roadblocks.

Lockheed Martin has demonstrated the benefits of a tool suite for its work on the Joint Strike Fighter initiative, which provided such useful outputs as facility requirements, floor space requirements, factory layout, visual flow of factory operations, and more. Hewlett-Packard demonstrated the cost savings and productivity

improvements from improved information flow within its organization, one of the goals of manufacturing modeling and simulation.

Important features of modeling and simulation software packages include flexibility, user interface, model execution speed, import/export capability, iterative capability, combined discrete-continuous simulation, evoking external routines, animation, and statistical capabilities. Seven commonly available simulation software packages are evaluated and compared based on these and other criteria.

Developing standards for improved interoperability of tools and expanding the base of scientific knowledge in manufacturing are seen as key issues for advancing the state and usage of manufacturing modeling and simulation in the future.

## **I. STATE OF THE ART IN MANUFACTURING MODELING AND SIMULATION**

Modeling and simulation (M&S) is emerging as a key tool in the field of manufacturing. This tool offers product developers the opportunity to improve products, perfect processes, reduce design-to-manufacturing cycle times, and reduce product realization costs. Instead of engaging in a lengthy process of building prototypes, testing them and modifying the design, product developers can use modeling and simulation tools to optimize the design and processes before a single prototype is built. These same tools can help improve the efficiency and cost-effectiveness of manufacturing processes. Tools that are used for these purposes are referred to as "manufacturing modeling and simulation."

The most progressive development programs have demonstrated the benefits of using modeling and simulation to accomplish such objectives as reducing time to market, improving producibility, estimating life-cycle costs, and meeting customer needs and expectations at lower cost. Nevertheless, the manufacturing modeling and simulation toolset is not well developed. Even the leading practitioners are limited by the capabilities of available tools; the most robust models today are little more than a geometric representation coupled with limited product definition and manufacturing information. Tools are poorly integrated so that thorough modeling of a complex product today requires the creation of multiple models of different types, none of which work together.

Despite these limitations, progress is being made. Knowledge-based systems and automated advisors are increasing in use, helping designers to make better decisions when using modeling and simulation tools. The semiconductor industry has done a superb job of developing tools and technologies to support its needs in moving from concept to manufactured product. The continuous processing industry has for many years improved product quality and made its processes more effective through manufacturing modeling and simulation. More recently, the aerospace and automotive industries demonstrated reduced time-to-market and cost savings through digital, model-based design and manufacturing techniques for products such as the Boeing 777 and the Dodge Viper.



Modeling and simulation in manufacturing process applications is often used to help diagnose a problem but is rarely used as the method to create and optimize process and product designs. However, in a demonstration by Pratt & Whitney for the joint DOE/Industry Technologies Enabling Agile Manufacturing (TEAM) program, simulation tools were used to optimize the design of a forming process for jet engine nozzle panels. A 6:1 reduction in design-to-manufacturing cycle time was achieved.

Standards are a barrier to the creation and use of manufacturing modeling and simulation tools; no good standards exist to ensure compatibility between manufacturing M&S tools and the rest of the systems that support any given manufacturer's product design and manufacturing environment. Also, a good fundamental understanding of the scientific basis for most manufacturing processes does not exist to build the models.

#### **A. WELL-DEVELOPED TOOLS**

Certain manufacturing M&S functions are better developed than others. Below is a discussion of capabilities for which tools are relatively well developed.

*Physical representation:* Modeling of physical objects is the most common and well-developed application of computer modeling technology. A number of specialized tools and systems have developed to enable direct output of manufacturing data to drive actual manufacturing process equipment. Problems are caused, however, by the ability of modeling systems to create mathematical shapes that cannot be manufactured.

*Performance:* Specialized applications, such as finite element analysis tools, are used to custom-build mathematical models to evaluate performance in different operational regimes of temperature, pressure, stress, and similar factors. Functional performance modeling of electrical circuitry, which relies on a large base of validated component models and a handful of popular simulation codes (SPICE, etc.), are quite well developed. Simulation codes are also used extensively for such specialized needs as aerodynamic (e.g., for airframes and aerostructures) and hydrodynamic (e.g., submarine hulls and control surfaces) performance evaluation, but do not provide enough confidence to replace prototype testing.

*Producibility:* Increasingly sophisticated 3-D modeling tools are enabling designers to see how complex parts fit together and modify problematic designs to make them easier to fabricate and assemble. Designers are increasingly able to attack traditional producibility barriers such as parts count, fastener complexity,

curing/annealing schemes, and ease of assembly. Dynamic modeling of a part of an item of material in the production process can be done, although with limited fidelity. In most enterprises, optimizing a product for producibility still depends largely on trial-and-error manufacturing.

*Material Preparation:* M&S applications for material processes are highly niche specific. Advanced analytical techniques are being applied successfully for many material preparation activities, particularly in continuous processing industries.

*Material Treatment:* There are modeling systems that can assist in curing process selection and design, although this is normally based largely on human experience and judgment. An example is the advisory system for electroplating, electroforming, plasma spraying and similar operations developed by Lockheed Martin at DOE's Oak Ridge Y-12 Plant. The system uses material deposition models and product geometry to automatically design the cells and shielding to be used in the process.

*Material Forming:* Many excellent tools and applications exist, the most popular of which is finite element meshes. Modeling and simulation has been successfully applied for deformation of metallic parts, but additional materials and processes have not been included. Knowledge-based systems coupled with modeling and simulation tools are creating design advisors that produce dies that "get it right the first time." Neural networks, trained through models and empirical data, are being extended as accurate predictors of forming performance.

*Material Forming/Addition:* Material removal is probably the best understood of all manufacturing processes. M&S tools based on metallurgical principles have predicted optimum machining parameters for efficient cutting. Material addition technologies are flourishing, aided by advanced modeling and simulation capabilities. A few years ago, stereolithography was a revolutionary technology. Today, new solid free-form fabrication techniques, driven by very precise 3-D models are producing real parts from real materials.

*Assembly/Disassembly/Reassembly:* Modeling and simulation is now used routinely to optimize product and process designs for efficient assembly of complex products. Assembly modeling is well developed for rigid bodies, and tolerance stack-up is well addressed in limited applications. High-level models of assembly operations are common in continuous process industries.

*Quality, Test and Evaluation:* Methods have been developed, such as probabilistic mechanics methods by the Nuclear Regulatory Commission and Southwest Research Institute, but unfortunately these methods have not penetrated many industries. Modeling and simulation for dimensional metrology is increasing. Tools such as Cimstation from Silma Corporation and Valysis from Technomatics, and the acceptance of Dimensional Measurement Interface Standard (DMIS) as a standard for coordinate measuring machine (CMM) programming, have had great impact. Simulation of toolpaths before inspections are performed is now common in many companies.

*Packaging:* Modeling and simulation is playing a major role in the transformation of packaging. Logistics models and part tracking systems help ensure the proper packaging and labeling for correct product disposition. Modeling and simulation is critical in designing packaging to assure product protection and for the design of multifunctional packages to replace the separate functions of packaging.

## **B. SIGNIFICANT LIMITATIONS**

While there are a number of well-developed tools in manufacturing modeling and simulation today, there are significant limitations that prevent the tools from reaching their full potential for optimizing design. Most importantly for manufacturing M&S, knowledge of the underlying physics of most material and transformation processes is not complete. The tools available today offer limited ability to capture and reuse knowledge about a product, and few tools or methods are available that enable product designers to take organizational, social, or other nonphysical factors into account.

Attempts at improving the interoperability of process M&S tools are frustrated by grossly incomplete data representations as well as incompatible data structure and representation formats. Limitations of some specific functions are discussed below.

*Physical representation:* Current tools cannot support the integration and application of transformations from design features to manufacturing features. The modeling languages do not capture design intent, and non-geometric issues such as environmental considerations and materials of composition are not well addressed.

*Performance:* Product performance modeling for mechanical systems is limited in most industries. Little capability exists to model and simulate complex interactions outside of highly specialized aerospace and defense applications. Existing performance modeling applications are not adequate to capture all the knowledge about the product or

the processes to design or produce it. Only a few tools are offered that can analyze a product in the context of its actual use to help optimize designs for ease of use and other considerations. Finally, the fundamental physics of actual product and material characteristics are not understood in most domains.

*Cost/Affordability:* There are no good M&S tools for estimating costs for conceptual designs or determining to what extent a given design is affordable. Cost models are difficult to create because of poor traceability between estimated and actual costs and limited understanding of cost interdependencies. They are traditionally developed in "bottom-up" fashion by estimating design and manufacturing costs for individual components, materials, and their assembly; test; packaging; and handling. Estimates are based largely on experience and intuition. Top-down estimating, in which a target cost is established first and then decisions are made based on that target, is often the only way to bring a product to market with acceptable profit margins.

*Producibility:* Models are limited to assessments based on parts count, number of part surfaces, or known chemistry. There are no truly robust M&S tools for evaluating and optimizing producibility in a systematic fashion. There is little fundamental understanding of the physical phenomena related to producibility. Existing product models cannot be imported directly into process models for evaluation of interactions at the micro or macro level.

*Life Cycle Requirements:* There are few tools to provide feedback (about such things as field supportability, effectiveness of training, and environmental suitability) from point of use to the design function.

*Material Preparation:* Most of the applications are based on empirical data, and supporting scientific understanding is limited. The fundamental science of distortion, residual stress, phase transformations, and similar factors is not well understood.

*Material Treatment:* Modeling and simulation is used here in only limited, well-defined applications. Better tools for modeling the total behavior of processes and their effects are needed.

*Material Forming:* Successful applications of modeling and simulation have generally been limited to deformation of metallic parts. Tools for modeling of fibrous structures, cellular solids, polymer paper laminates, and composites are very limited. Powder metallurgy, rolling, stamping, and forging are not nearly as well addressed as more traditional metal-forming operations.

*Material Removal/Addition:* While traditional applications are well understood, microprocesses, electrochemical machining, laser cutting, very high-speed machining, and water-jet cutting, as well as ceramics and certain composites, are not well understood.

*Assembly/Disassembly/Reassembly:* Material handling is a critical element of assembly modeling, but models that focus on this are usually very simple in their treatment. Design of assemblies for disassembly, refurbishment, reuse, or recycling is seldom included in the modeling objectives of support by M&S applications.<sup>1</sup>

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<sup>1</sup> IMTR M&S Workshop Group and IMTR Roadmapping Project Team, *Integrated Manufacturing Technology Roadmapping Project: Modeling and Simulation*, Oak Ridge Centers for Manufacturing Technology, Oak Ridge, TN, Chapters 2-3.

## **II. USES OF MANUFACTURING MODELING AND SIMULATION IN INDUSTRY AND GOVERNMENT**

### **A. LEAN AEROSPACE SURVEYS**

A Defense Systems Management College study in 1994 examining the overall state of modeling and simulation within ACAT I and II programs found that manufacturing modeling and simulation tools were used most frequently for the following purposes (by number of applications):

1. Requirements (high)
2. Testing (high)
3. Costs (moderate)
4. Threat (low)
5. Programmatic (low)
6. Supportability (low)
7. Producibility (low)
8. Environmental (low)

The roles of manufacturing modeling and simulation in requirements, cost, and producibility are discussed below.

#### **1. Requirements Generation**

Although the survey results show that manufacturing modeling and simulation tools are being used extensively in requirements generation, their effectiveness is largely undocumented and areas of high leverage are unknown. No return-on-investment measures are being used to justify the payoff or existence of manufacturing M&S tools.

However, other surveys conducted by the Lean Aerospace Initiative at the Massachusetts Institute of Technology show how and why manufacturing M&S tools are used in the requirements generation process. These surveys were distributed to more than 14 large military programs and their industry contractors, as well as members of the

military user community. When asked to describe their rationale for using manufacturing M&S in requirements generation, respondents answered as follows:

1. Perceived net benefit
2. Necessary to be competitive
3. Contractual requirements
4. Dictated by Policy

Survey respondents most commonly cited a perceived overall benefit as the reason for using manufacturing M&S tools. In fact, when asked to rate on a 7-point scale the overall usefulness of manufacturing M&S in generating system requirements, 79 percent of respondents rated it 6 or 7. The two most commonly cited specific benefits were establishing performance ranges and verifying requirements. Similarly, the two most commonly cited product and program benefits were rapid, early proof of concept and technical risk reduction.

When asked how manufacturing M&S competencies were prioritized in their overall plans, the respondents ranked them as follows:

1. M&S information available at the right place and right time
2. Implementing lessons learned
3. Reusing M&S tools
4. Using M&S information in the Integrated Product and Process Development (IPPD) environment
5. Creating M&S tools for re-use in the future

It is interesting to note that the creation of tools for reuse in future projects gets lowest priority, since manufacturing M&S is not project specific and requires considerable development time to be useful.

Another finding from the survey is what tools are being used. The results show that all of the space-related programs responding were primarily dependent on functional simulation for evaluation of their system requirements. Aircraft programs use and rely on physical simulation a great deal more, possibly because physical layout, structure, and appearance are generally considered more significant in aircraft programs.

## **2. Cost Modeling**

In the DoD Modeling and Simulation Master Plan (1995), it was expected that manufacturing modeling and simulation would help estimate life-cycle support and costs for systems. Most of these costs are committed early in the program, where modeling and

simulation is one of the few tools available. In fact, it is estimated that 70 percent of life-cycle costs of a program are committed to during requirements generation.<sup>1</sup>

Cost information early in the design process can help designers make important cost/performance trade-off decisions before committing to major features or specifications. The ideal tool would be a computer-aided design/computer aided manufacturing (CAD/CAM) system linked to an easily accessible cost tool that automatically allocates cost to the product being designed as each feature is developed. Research shows that a few organizations have embraced this vision of data commonality.

In fact, a survey shows the following percentages of companies that use links between design tools and other information:

1. Manufacturing (73 percent)
2. Military Past Design (70 percent)
3. Process (70 percent)
4. Past Design (55 percent)
5. Support Operations (38 percent)
6. Cost Accounting (30 percent)

It was found that companies that have good design/cost database commonality make cost/performance trade-off decisions one to two stages earlier than those without. In addition, the average number of cost overruns and the frequency of schedule overruns are lower when database commonality is in place. Other benefits of commonality revealed in interviews with organizations that achieved commonality include better assurance of ability to manufacture, better correlation between design and final product, and reduced paperwork.

Organizations may use empirical costs, including material costs, assembly costs, process capability and yields, subcontractor costs, capital costs, and support costs, as inputs to the cost models.<sup>2</sup> In cases where empirical data are not available, costs may be estimated through complexity theory, although it is not clear that this is common practice.

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<sup>1</sup> Myles Alexander Walton, "Identifying the Impact of Modeling and Simulation in the Generation of System Level Requirements," Thesis for degree of Master's of Science in Aeronautics and Astronautics, Massachusetts Institute of Technology, June 1999.

<sup>2</sup> David P. Hoult, C. Lawrence Meader, John Deyst, Jr., and Maresi Berry-Dennis, *Cost Awareness in Design: the Role of Data Commonality*, White Paper #LEAN 95-08, Lean Aerospace Initiative, Massachusetts Institute of Technology, November 1995.



Elements such as database, CAD, cost modeling, and validation are most likely to be linked by creating a virtual database using object-oriented technology. There are a few commercial tools available that link the design system and the cost model. Some cost modeling software, such as that offered by Cognition, includes a shell for a knowledge-based expert system that can warn of poor design decisions with a link to Pro/Engineer, a CAD package.

One of the more difficult issues in developing database commonality is feature mapping. Since there are a number of different processes that could be used to create the same feature, there may be a number of different cost estimates. This is not a problem, however, when building from standard components using well-understood processes since it is easy to identify the single best manufacturing process for a feature. Especially in advanced military equipment programs, the processes may be quite new and difficult to quantify.<sup>3</sup>

### **3. Process Capability Databases**

Cost and performance are not the only trade-off decisions that are important in a development program. It is also necessary to choose design features based on the predicted quality and producibility of the final product. Research shows that companies have created process capability databases that can aid in making these decisions; in fact, 93 percent of responding companies have some type of process capability database (PCDB). However, it is typically used on only 14 percent of projects and 88 percent of responding companies use it less than 30 percent of the time.

Interviews find that PCDBs are being successfully used in manufacturing to monitor processes but generally are not being used to improve design. Some reasons given by companies for developing PCDBs include process monitoring, inspection and regulatory requirements, corporate metrics, dimensional management, and variation simulation analysis.

Nevertheless, 85 percent of survey respondents say that they would like to use internal PCDBs in design for the following purposes:

1. Designing parts with more appropriate tolerances

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<sup>3</sup> David P. Hoult and C. Lawrence Meader, "Methods of Integrating Design and Cost Information to Achieve Enhanced Manufacturing Cost/Performance Trade-Offs," Lean Aerospace Initiative Web site.

2. Identifying areas to apply robust design, specify realistic tolerances, and enable design quality verification prior to production
3. Generating exception reports for characteristics that do not meet six sigma
4. Building a "lessons learned" database that could be accessed by any work site
5. Designing out variation when required
6. Establishing tolerances and key characteristics for a product
7. Making products more producible
8. Making designs more robust
9. Simulating variation
10. Prioritizing process improvements
11. Understanding the cost impact of parameter values

Survey respondents said that the ideal PCDB would link directly to CAD and simulation software, automatically cautioning designers when a feature of manufacturing process being considered will not meet established quality levels. The ideal program would also enable plots of cost and cycle time versus performance.

The research identified many important barriers to the use of PCDBs in design. For instance, the databases are poorly populated with part information or process information in an inappropriate format for design needs. A lack of interoperability and compatibility among systems was also cited; even within the same enterprise, incompatible systems may be used. For instance, ACCESS (used by 27 percent of respondents), ORACLE (23 percent), and QUANTUM (32 percent) have incompatible indexing schemes.

The research found that poor links between PCDBs and other information systems is a significant barrier to PCD usage in design. Even where links do exist, they are usually less than fully integrated; most are simply pointers from the database to another system. Of the companies surveyed, 68 percent had no links at all. The rest had links from PCDBs to the following systems:

1. Measurement systems (29 percent)
2. Statistical graphics (13 percent)
3. Part drawings (13 percent)
4. Control plans (13 percent)

Other barriers to PCDB usage in design include the following:

1. Lack of management support – cited by 61 percent of respondents
2. Lack of usage metrics
3. Poor user interfaces

4. Poor PCDB indexing scheme – based on part number, not feature, material or characteristics (useful for designers)
5. No incentives to use PCD<sup>4</sup>

Seven technical issues hampering the use of process capability data by the design community were identified through questionnaires:

1. PCD provided as point value without uncertainty range.
2. Presented numerically rather than graphically
3. No consistent PCDB structure, makes interfaces and indexing schemes difficult to use
4. User can choose infeasible (impossible) indexes.
5. No method to obtain alternative data when the desired index is unpopulated
6. No methods to display aggregate data (when specifics of a part are not yet known)
7. No methods to eliminate outlier data or to combine runs.

## **B. CASE STUDY: LOCKHEED MARTIN**

Since 1996, Lockheed Martin has increased its use of manufacturing modeling and simulation tools because of their desire to reduce assembly span and costs. The initial tool suite used by Lockheed Martin included an “off-the-shelf” process planner, a factory/discrete event simulation, an assembly simulation, and variation management studies. This tool suite was adequate, but an improved process planner was desired.

The tool suite used the following inputs:

1. 3-dimensional models of engineering parts, machinery, tooling, etc. from CATIA or AutoCAD.
2. Manufacturing plan process flow
3. Learning curve
4. Direct labor
5. Span of component
6. Program schedule
7. Cost from cost simulation

The manufacturing modeling and simulation tools provided the following outputs:

1. Facility Requirements
2. Floor Space Requirements
3. Factory Layout

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<sup>4</sup> Melissa M. Tata and Anna C. Thornton, “Process Capability Database Usage in Industry: Myth vs. Reality,” Lean Aerospace Initiative Web site.

4. Visual flow of Factory Operations
5. Similar outputs from the discrete event simulation

Lockheed Martin used the software to validate the assembly sequence and to create visual training aids using mannequins and text boxes. They also used it to answer questions such as the following:

1. How much of the paint facility resources are consumed?
2. Must the assembly area be double decked to meet floor space requirements?
3. How will components flow through the factory?
4. How would the factory or component area look?

As a result of this experience, the following needs were identified:

1. Connectivity between Product Development Model (PDM) and the simulation tools. When CAD elements change in the PDM, the simulation engineer is notified and coached through an interactive update
2. Low-cost methods for storing, viewing, and maintaining simulations in the PDM over the life of a program
3. A knowledge base integrated into the simulation tool to help establish objectives
4. Output reported in layman's terms
5. Linkages from ERP to discrete event simulation
6. Simulation data collection integration into a manufacturing execution system (MES)

In addition, Lockheed Martin found that many "off-the-shelf" simulation tools are not ready for aircraft applications, and that it is useful to have tool developers join an Integrated Product Team in order to help with customization.<sup>5</sup>

### **C. CASE STUDY: HEWLETT-PACKARD**

Hewlett-Packard's (HP's) experience shows the tangible benefits of information—such as that which manufacturing modeling and simulation tools can provide—to the product development process. HP developed an information infrastructure that facilitates such objectives as worldwide virtual collocation, IPPD teams, seamless flow of information throughout the design process, and standards to reduce costs and improve the ability to share designs, engineers, and processes. Integrated modeling and simulation for design and manufacturing is part of an overall

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<sup>5</sup> Guy S. Gordon, "Modeling and Simulation: Progress, Needs, Opportunities," presentation to Defense Manufacturing Conference, November 29, 1999.

information infrastructure that allows engineers to focus on product development tasks rather than spending time on tool development, format translations, or rework.

Hewlett-Packard's information infrastructure supports a focus on core product development-related business processes. Any processes that exist for reasons other than to support the business objectives and environment are not considered "lean" and are not supported. HP's infrastructure is built and maintained according to architectural principles, such as the following:

1. Infrastructure elements must be interchangeable
2. Infrastructure will be based on industry standards
3. Information will pass seamlessly through the environment
4. There will be a single master source for each information element

This information infrastructure initiative has produced significant return on investment for Hewlett-Packard. For example, the proportion of revenue from products that were less than 2 years old increased to two-thirds by 1997, indicating that products were being developed quickly, introduced effectively, and marketed successfully. HP also saw its net revenue per employee double from 1991 to 1997 thanks to information flow. At the same time, its research and development expenditures dropped from 10 percent of revenue to about 7 percent from 1992 to 1996.

While these benefits may be due only in part to improved information flow, these results show the possible benefits of modeling and simulation in helping to facilitate the flow of information in product development.<sup>6</sup>

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<sup>6</sup> Hewlett-Packard Company, "Information Infrastructure for Rapid Product Development," presentation to LAI Fall Plenary Meeting, Product Development Tools Session, October 1998.

### III. SIMULATION SOFTWARE TOOLS

#### A. FEATURES AND CAPABILITIES

In order to discuss the advantages and disadvantages of currently available simulation software, it is important to define and outline common features and capabilities. Here are some general capabilities and their relevance.

*Flexibility:* A simulation package that relies on a fixed number of constructs must be inadequate for certain systems encountered in practice. "Flexibility" refers to the ability to create new modeling constructs and to modify existing ones. The software can offer such flexibility by allowing users to define and change attributes for entities and global variables, to use decision logic, and to use mathematical expressions and functions in the simulation.

*User Interface:* While modeling constructs must be highly configurable, they also must not overwhelm the user with information that obscures the useful output of the simulation. Use of graphical user interfaces and hidden dialogue boxes or other tools helps manage information on the screen and make the simulation accessible to non-expert users. Similarly, hierarchy makes software easier to use by allowing users to combine several basic modeling constructs into a new higher-level construct that can be catalogued and used in future models. Debugging aids should be interactive and intuitive.

*Model Execution Speed:* When a large number of entities must be processed, fast execution speed is crucial to the usefulness of the simulation product.

*Import/Export capability:* The ability to import data from or export data to another application, such as a database or spreadsheet, makes the information easier to process and manage.

*Iterative Capability:* It is desirable for a simulation package to be able simulate automatically different scenarios that iterate on some model parameter, and then plot some performance measure as a function of the parameter being iterated.

*Combined Discrete-Continuous Simulation:* Sometimes it is necessary to have certain capabilities from continuous simulation available to a discrete-event simulation.

*Evoking external routines:* This ability makes it easier to integrate a complex set of logic that is written in a programming language into a simulation.

*Animation:* In software that features built-in animation, key elements of the system are represented on the screen by icons that dynamically change position, color, and shape as the simulation runs. The best animation features high-resolution icons, a library of standard icons, smooth movement, control for speed of movement, a zoom feature to increase the detail of a display, and dynamic graphics and statistic displays that are updated in real time as the simulation progresses. Vector-based graphics (as opposed to pixel-based graphics) allow objects to be rotated and to maintain proper orientation when turning a corner. Three-dimensional animation allows the vantage point of the view to be rotated around three axes, a useful capability for situations in which vertical clearances are important.

Some of the uses for simulation are as follows:

1. Communicating the output of the simulation in a clear and intuitive way
2. Debugging the simulation computer program
3. Showing improvements to a procedure that cannot be ascertained from numerical results
4. Training operational personnel
5. Promoting communication among the project team

*Statistical capabilities:* It may be difficult or impossible to obtain correct results from a simulation if the software does not have good statistical-analysis features. A mechanism is needed for generating random numbers with at least 100 different streams that can be assigned to different sources of randomness. The software should be programmed with both discrete and continuous probability distributions, rather than just a perceived mean value, to represent each source of randomness. The best software offers a single command to make independent replications of the simulation model, with each run using separate sets of random numbers but the same initial conditions. Then, variances and standard deviations can be calculated using data from runs that are independent but probabilistic copies of each other. An optimization module can determine through iteration what combination of the decision variables produces an optimal or near-optimal solution. The software should be able to show which input factors have the greatest impact on the performance measures of interest and also what the interactions among the factors are.

## B. COMPARISON OF SEVEN TOOLS

Table 1 lists seven software packages designed for use in manufacturing-oriented and general-purpose simulations.

**Table 1. Seven Simulation Software Packages**

Software	Producer	Uses
WITNESS	Lanner Group	Manufacturing oriented
ProModel	PROMODEL Corp.	Manufacturing oriented
EXTEND	Imagine That	General purpose
Taylor Enterprise Dynamics	F&H Simulations	Manufacturing oriented
Arena	Systems Modeling Corp.	General purpose
AutoMod	AutoSimulations	Manufacturing oriented
MODSIM III	CACI Products	Object oriented; greatest benefits for large and complex models

Table 2 compares the modeling constructs and procedures for using them in each package.

**Table 2. Modeling Constructs and Procedures**

Software	Model Constructs	Other Constructs	Building a Model	Customization
WITNESS	Parts, machines (or locations) buffers (queues), labor (workers or tools)	Material handling: conveyors, forklifts, AGVs, tanks and pipes	Use graphics, pull-down menus, and dialog boxes; also rules (for input, output) and actions (when event occurs)	
ProModel	Locations (machines), entities (parts), arrivals, processes, resources	Material handling: conveyors, forklifts, AGVs, bridge cranes, tanks	Use graphics, fill in fields, use internal or external language	Internal and external languages
EXTEND	Blocks available from libraries (discrete event, generic, statistics)	Manufacturing Process and Business Process Reengineering	Select blocks, connect to indicate flow of entities, add details	Internal ModL language to customize blocks, create new ones



**Table 2. Modeling Constructs and Procedures (Concluded)**

Software	Model Constructs	Other Constructs	Building a Model	Customization
Taylor Enterprise Dynamics	"Atoms": servers, queues, conveyors, probability distributions, etc.		Drop atoms onto window, add details; use internal language or call external routines	4Dscript language to create new atoms
Arena	"Modules": arranged in templates, such as Basic Process, Advanced Process, and Advanced Transfer	Several kinds of material handling devices, forklift trucks, and AGVs	Select modules, connect to indicate flow of entities, add details	Construct custom modules from standard arena modules; store in template
AutoMod	Constructs include loads (parts), resources (machines/workers), queues, processes (logic), material handling	Tanks and pipes	Combination of graphics, dialog boxes, programming; input layout graphically	
MODSIM III	Modules: one main plus definition and implementation for each object type		Methods: ask (procedure) and tell (process)	

Table 3 describes the general capabilities of each software package in more detail.

**Table 3. General Capabilities of Simulation Software**

Software	Hierarchy	Animation	Cost Model	Interface
WITNESS	Unlimited	Default 2-D; optional 3-D	No	
ProModel		2-D	Can assign costs to constructs	Active X capability; custom interfaces
EXTEND	Unlimited; can use inheritance	Standard 2-D; optional 3-D		Notebook can be used as front end or results display
Taylor Enterprise Dynamics	Unlimited		Profit for each part; cost associated with machines, labor work-in-process, etc.	

**Table 3. General Capabilities of Simulation Software (Concluded)**

Software	Hierarchy	Animation	Cost Model	Interface
Arena	Unlimited	2-D; displays dynamic graphics	Activity-based costing; provides value-added and nonvalue-added cost and time reports	Visual basic allows data transfer to other applications such as Excel, user-friendly interfaces, customized reports, interface with Visio drawing package
AutoMod		3-D		
MODSIM III		2-D and 3-D		

Table 4 compares the statistical features of each simulation package.

**Table 4. Statistical Features of Simulation Software**

Software	Standard Random Number Streams	Standard Probability Distributions	Analysis Tools	Point Estimates, Confidence Intervals
WITNESS	100	Theoretical and empirical	Time plots, histograms, and pie charts	Yes
ProModel	100	Theoretical and empirical	State diagrams, histograms, and time plots	Yes
EXTEND	Unlimited	Theoretical and empirical	Histograms, time plots	Yes
Taylor Enterprise Dynamics	Unlimited	Theoretical and empirical	Time plots, histograms, bar charts, pie charts, and Bantt charts	Yes
Arena	Unlimited	Theoretical and empirical	Histograms, bar charts, time plots, correlation plots	Yes
AutoMod	Unlimited	Theoretical and empirical	Bar charts, pie charts, time plots, AutoStat module	Yes
MODSIM III	Unlimited	Theoretical and empirical		Not built-in but can be programmed

Table 5 compares the optimization features of each package.

**Table 5. Optimization Features of Simulation Software**

Software	Time to failure	Independent Replications	Optimization
WITNESS	Based on busy time, calendar time, or number of parts	Optional	Optional module
ProModel		Yes	SimRunner2 optimization module
EXTEND	Based on busy time by default, but others available	Yes	Optimization module in development
Taylor Enterprise Dynamics		Yes	OptQuest module available as an option
Arena		Yes	OptQuest optimization module available as an option
AutoMod		Yes	Autostat module does optimization
MODSIM III		Not built in but can be programmed	

**APPENDIX A**  
**REFERENCES**

## Appendix A

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**APPENDIX B**  
**GLOSSARY**

## **Appendix B**

### **GLOSSARY**

3-D	Three-dimensional
ACAT	Acquisition Ccategory
AGV	Automatic Guided Vehicle
CAD	Computer-aided Design
CAM	Computer-aided Manufacturing
CMM	Coordinate Mmeasuring Machine
DMIS	Dimensional Measurement Interface Standard
DOE	Department of Energy
IMTR	Integrated Manufacturing Technology Roadmapping
IPPD	Integrated Product and Process Development
M&S	Modeling and Simulation
PCD	Process Capability Data
PCDB	Process Capability Database
PDM	Product Development Model
TEAM	Technologies Enabling Agile Manufacturing

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13. ABSTRACT (Maximum 200 words) This paper provides an overview of manufacturing modeling and simulation, which includes applications to improve the performance, manufacturability, quality, and cost of products. The paper examines reviews of the emerging state of the art in manufacturing modeling and simulation, studies based on surveys of government and industry product development offices, and information from companies that use modeling and simulation directly to enhance their product development efforts. The research finds that manufacturing modeling and simulation is making great progress toward the vision of a rich toolset that fully integrates with design tools and supports a smooth flow of useful information throughout the organization. Important features of modeling and simulation software packages include flexibility, user interface, model execution speed, import/export capability, iterative capability, combined discrete-continuous simulation, evoking external routines, animation, and statistical capabilities. Seven commonly available simulation software packages are evaluated and compared based on these and other criteria. Developing standards for improved interoperability of tools and expanding the base of scientific knowledge in manufacturing are seen as key issues for advancing the state and usage of manufacturing modeling and simulation in the future.			
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